Possible evidence for "dark radiation" from Big Bang Nucleosynthesis Data

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(February 1, 2008)

We address the emerging discrepancy between the Big Bang Nucleosynthesis data and standard cosmology, which asks for a bit longer evolution time. If this effect is real, one possible implication (in a framework of brane cosmology model) is that there is a "dark radiation" component which is negative and makes few percents of ordinary matter density. If so, all scales of this model can be fixed, provided brane-to-bulk leakage problem is solved.

arXiv:hep-th/0512038v2 6 Feb 2006

In this paper we discuss the emerging discrepancy between Big-Bang Nucleosynthesis (BBN) calculations and measurements. The facts themselves are rather well known. For example, in recent summary of the BBN data analysis can be found e.g. in [1] who conclude that "effective number of extra neutrinos", as it is usual to put it, does not want to go away and tends to be negative. The final numbers these authors give is

$$\Delta N_\nu = -0.65 \pm 0.35 \tag{1}$$

Account for other forms of matter naturally make the discrepancy larger, for example see the effects of right-handed neutrinos [2].

Thus, formally speaking, the effect is about two standard deviations, and in principle one may not worry about it yet. However, in this letter we propose to take another attitude, consider it to be real effect and discuss what it potentially may mean, either for physics or cosmology, which we now discuss subsequently.

Variable physical constants is one possibility to explain the anomaly. One may take the following attitude: if the deviations are not some systematics in part of the data but a real effect, it should be possible to find its origin by letting main parameters of the BBN program to be fitted freely, unconstrained to the today's value, and see if it results in much better fit of all the data. This was found indeed to be the case, and the best results were obtained if the varied quantity is the *deuteron binding* Q_d [3]. Its variation by

$$\delta Q_d/Q_d = -0.019 \pm 0.005 \tag{2}$$

leads to much better fit of all the same data (and thus the effect makes larger number of standard deviations). On top of that, this change leads to excellent agreement for baryon-to-photon ratio η between this fit and the best fit to Cosmic Microwave Background (CMB) data.

The deuteron binding is not just one of the parameters; in fact it was identified in our papers [4] as part of the chain which is the most sensitive way to test possible variation of weak-to-strong scales. The above mentioned variation of Q_d corresponds to only 10^{-3} variation of the strange quark to QCD scale* $\Delta(m_s/\Lambda_{QCD})/(m_s/\Lambda_{QCD})$. The description of the corresponding enhancement factors which lead all the way from this small variation to that of deuteron binding and eventually to quite noticeable variation of He^4, Li^7 production can be found in these papers.

Deviations from standard cosmology†. One may try to ascribe the discrepancy to an *increase* of the total time allocated to BBN nuclear reactions (e.g. more neutrons should decay).

The first obvious suspect is the cosmological scalar field (quintessence [5]), which may or may not be related to either inflation-era scalar or to present-day acceleration, see discussion e.g. in [1]. But, if so, one would need to have an opposite sign of its effective potential, which is quite difficult to reconcile with other constraints.

Brane Cosmology much discussed in literature is another attractive option. We restrict this discussion to the simplest version of it, with a single brane in multi-dimensional space.

The unavoidable consequence of gravity propagating in extra dimension is a sort of back reaction on the cosmological evolution as observed on the brane. New terms due to second order effects in density and due to bulk gravity field appear in effective evolution equation on the brane, see [6] and a review in [7]

The parameters of the model include the 4-d brane tension $\lambda = M_\lambda^4$, the 5d cosmological constant Λ, and the 5d gravity coupling $\kappa_5^{-2} = M_G^3$. One relation between them is need to be fine-tuned to get effective cosmological constant to a small value of λ_4 (to be ignored at BBN time we discuss). Another relation is to fix the Newton constant $G_N = \kappa_5^4\lambda/48\pi$. That leaves us with one free parameter to be fixed.

The resulting evolution equations of the model can be written (see review [7] and references therein) in the following convenient form

*Or, if one prefers, a twice smaller variation of the kaon to nucleon mass ratio.

†By standard we mean textbook cosmology with matter consisting of photons and 3 massless neutrinos.

$$\dot{\rho} + 3(1+w)\,\frac{\dot{a}}{a}\,\rho = -T^{leak} \tag{3}$$

$$\dot{\chi} + 4\,\frac{\dot{a}}{a}\,\chi = T^{leak} \tag{4}$$

$$\frac{\dot{a}^2}{a^2} = A\rho^2 + \frac{8\pi}{3M_P^2}(\rho+\chi) - \frac{k}{a^2} + \lambda_4 \tag{5}$$

where M_P is the Plank mass and $w = p/\rho$ is the usual matter equation of state. The dots stand for derivatives with respect to cosmological time τ. k-term (due to curvature) and λ_4 are unimportant. The coefficient A of the quadratic term in density is suppressed compared to the linear term by very small parameter T^4/M_χ^4 where $T^4 \sim \rho$ is the temperature scale. The "dark radiation" term χ is the leading correction to standard cosmology, and it has the same evolution as radiation-dominated matter $w = 1/3$ (appropriate at both BBN and CMB times), and the term T^{leak} describes "leakage" of energy from the brane to the bulk which happens at early (noninear) stage. Note that $\rho + \chi$ is conserved.

Let us translate the BBN discrepancy in terms of χ

$$\frac{\chi}{\rho} = \frac{7}{43}\,\frac{\Delta N_\nu}{N_\nu} \approx -0.11 \pm 0.06 \tag{6}$$

where the number is for (1).

For expanding brane universe, it is quite natural [7] to obtain negative χ. The specific mechanisms of the "leakage" depend on details of the nonlinear evolution stage, for some model-dependent recent calculations see [8]. Note that our results are consistent with the limits on ρ/χ which have been obtained earlier [9].

Implications.

The main consequence one can draw from possible observation of "dark radiation", if confirmed, would be a definite magnitude for the "leakage" term, potentially capable to fix the remaining scale ambiguity of the model.

Note that the number of effective degrees of freedom in a Standard Model is reduced by about an order of magnitude, from early to BBN time. Therefore, χ, when produced, was even smaller correction to the ordinary matter density.

Another implication[‡] is because that both BBN and CMB times are in the radiation-dominated era, and therefore the same ratio χ/ρ should be kept. As detailed in [1], the current data on CMB do not contradict the same value of ΔN_ν, although their accuracy is less restrictive at this time. With better data on both BBN and CMB one can possibly test whether both will give the same value of χ/ρ. If not, the brane cosmology model may thus be rejected.

Suppose we take this literally and ask what implications this would have for earlier cosmology. Unlike the usual matter, which presumably was produced at the end of inflation era at some particular time, the "dark radiation" was produced gravitationally, perhaps much earlier, and its amount depends on such parameters as the number of extra dimensions. With a non-zero χ, one should seriously revise inflation scenarios.

VF appreciates support from the Australian Research Council, Department of Energy, Office of Nuclear Physics, Contract No. W-31-109-ENG-38 and State University of New York. We are grateful to Ken Nollett for useful comments.

[1] J. P. Kneller and G. Steigman, Phys. Rev. D **67**, 063501 (2003) [arXiv:astro-ph/0210500]. V. Barger, J. P. Kneller, H. S. Lee, D. Marfatia and G. Steigman, Phys. Lett. B **566**, 8 (2003) [arXiv:hep-ph/0305075].

[2] A.D. Dolgov,Phys.Rept.370:333-535,2002; hep-ph/0202122

[3] V. F. Dmitriev, V. V. Flambaum and J. K. Webb, Phys. Rev. D **69**, 063506 (2004) [arXiv:astro-ph/0310892].

[4] V. V. Flambaum and E. V. Shuryak, Phys. Rev. D **67**, 083507 (2003) [arXiv:hep-ph/0212403]. Phys. Rev. D **65**, 103503 (2002) [arXiv:hep-ph/0201303].

[5] B.Ratra and P.J.E.Peebles, Phys.Rev.D37,3406 (1988), C.Wetterich,Nucl.Phys.B302, 668 (1988).

[6] T. Shiromizu, K. i. Maeda and M. Sasaki, Phys. Rev. D **62**, 024012 (2000) [arXiv:gr-qc/9910076].

[7] E. Kiritsis, Fortsch. Phys. **52**, 200 (2004) [Phys. Rept. **421**, 105 (2005)] [arXiv:hep-th/0310001].

[8] D.Langlois and L.Sorbo, Phys.Rev.D68 (2003) 084006, hep-th/0306281 M.Minamitsuji, M.Sasaki and D.Langlois, gr-qc/0501086

[9] K. Ichiki, M. Yahiro, T. Kajino, M. Orito, and G.J. Mathews. Phys. Rev D **66**, 043521 (2002); astro-ph/0203272. J.D. Bratt, A.C. Gault, R.J. Scherrer, T.P. Walker. Phys. Lett. B**546**, 19 (2002).

[‡]Unlike models with scalar fields, the "dark radiation" has rigidly fixed time evolution.